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19. ABSTRACT

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VISUAL PROCESSING IN TEXTURE SEGREGATION

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CONTENTS

1. ABSTRACT

Previous research showed that the outputs of 2D Gabor filter can account for much of the segregation of a periodic visual display into regions (Sutter, Beck, & Graham, 1989). Two nonlinearities were shown also to occur (Graham, Beck, & Sutter, 1989; 1990). One nonlinearity was an intensity dependent nonlinearity which can be accounted for by sensory adaptation occurring before the channels or by a compressive intracortical interaction among the channels (see Grossberg & Mingolla, 1985). The second nonlinearity was a rectification-like nonlinearity that is like that presumed to occur in complex cells (Spitzer & Hochstein, 1988). During the first year of AFOSR Grant 88-0320, research was completed showing that grouping processes, as well as the outputs of spatial-frequency/orientation channels, yield effortless spontaneous segregation. Two types of grouping were shown to yield effortless texture segregation: (1) the grouping of discrete elements into a line-line like pattern through alignment and equal spacing of the elements (Beck, Rosenfeld, & Ivry, 1989), and (2) the grouping of intermixed elements into subpopulations through lightness similarity (Beck, Graham, & Sutter, 1990).

During the second year of the grant, experiments were conducted further investigating the role of both spatial-frequency channels and grouping mechanisms in texture segregation. Patterns were constructed in which differences in the outputs of Gabor filters fail to account for the perceived segregation. Perceived segregation is, however, predicted by the outputs of DOG filters. The results suggest that there are at least two primitives for texture segregation: the outputs of concentric receptive fields (DOG filters) and of oriented receptive fields (Gabor Filters). We also compared the properties of 2D and 3D figures yielding effortless segregation. Changes in the orientations of a stimulus in which the slopes of the component features do not change, e.g., a 180 degree rotation of a stimulus, yields stronger segregation with 3D figures than with 2D figures. We hypothesize that the segregation differences are due to grouping processes. A 3D representation makes explicit the orientations of object surfaces enabling the grouping of 3D figures by the similarity of their surface orientations, e.g., the directions of their surface normals.

2. RESEARCH SUMMARY

2.1 Spatial Frequency Channels

2.1.1 *Introduction*

We and others have shown that the outputs of spatial-frequency/orientation channels with weighting functions like those of simple cells (Gabor filters) can account for much of the segregation of a visual display into regions (Beck, Sutter & Ivry, 1987; Bergen & Landy 1990; Chubb & Sperling 1988; Daugman 1987, 1988; Fogel & Sagi 1989; Grossberg, 1987; Klein & Tyler 1986; Malik & Perona 1989; Nothdurft 1985; Sutter, Beck, & Graham, 1989; Turner 1986; and Victor 1988). Two nonlinearities were shown also to occur. One nonlinearity was an intensity dependent nonlinearity which can be accounted for by sensory adaptation occurring before the channels or by a compressive intracortical interaction among the channels (see Grossberg & Mingolla, 1985). The second nonlinearity was a rectification-like nonlinearity that is like that presumed to occur in complex cells (Spitzer & Hochstein, 1988). A detailed discussion of these nonlinearities can be found in Graham, Beck, & Sutter, 1989, 1990. This past year we investigated

whether the processes yielding texture segregation do not also work on the outputs of concentric receptive fields. We have constructed patterns in which differences in the outputs of Gabor filters fail to account for the perceived segregation. Perceived segregation is, however, predicted by the outputs of DOG filters. The results suggest that there are at least two primitives for texture segregation, concentric receptive fields (DOG filters) and oriented receptive fields (Gabor filters). Adaptation studies of spot and bar patterns have also indicated the existence of separate orientation-selective and nonorientation-selective channels in the visual system (Naghshineh & Ruddock, 1978).

2.1.2 *Experimental Procedures and Theoretical Predictions*

The stimuli were computer generated patterns composed of four quadrants and were displayed for 1000 msec on a Tektronix RGB monitor. The elements in one quadrant differed from those in the other quadrants by a reversal of their contrasts, i.e., the light and dark areas of the elements were interchanged (see Figures 1 and 2). The discrepant quadrant appeared equally often in each of the four corners . A subject rated the segregation of the discrepant quadrant on a scale from 0 to 4. The areas of the light and dark regions composing an element were always equal. The procedure and instructions were similar to Sutter, Beck & Graham (1989). Ten subjects served in each experiment.

We hypothesized that the information for texture segregation are the *differences* in the mean and modulation of outputs in a channel when a channel (a receptive field weighting function) is convolved with the discrepant and non-discrepant quadrants of a pattern (Sutter, Beck, & Graham, 1989). The mean outputs of the discrepant and non-discrepant quadrants were similar and failed to correlate with perceived texture segregation. We, therefore, report only the differences in the modulation of outputs. The modulation of outputs in each channel was assessed by computing the standard deviation of the outputs for different spatial positions of the weighting function. The difference between each channels standard deviations to the discrepant and non-discrepant quadrants yielded a within channel difference for each stimulus. The within-channel differences were weighted by the contrast sensitivity function. Ratings of perceived segregation are assumed to be monotonically related to the combined within-channel differences. The graphs shown plot the square-root of the sum of the squares of the weighted within channel differences. The model is described in detail in Sutter, Beck & Graham (1989).

The on-center concentric receptive fields were modeled by a difference of Gausians. The overall diameters of the receptive fields were 11, 23, 45, 93, and 189 pixels giving a total of 5 channels. The diameter of the excitatory center of a receptive field was equal to the width of the inhibitory annulus. The spatial-frequencies of the channels were .5, 1, 2, 4, and 8 cycles/degree. The on-center even-symmetric oriented receptive-fields were modeled by two-dimensional Gabor functions after Daugman (1985) and Watson (1983). The spatial-frequency half-amplitude full-bandwith was one octave and the orientation half-amplitude full-bandwith was 38 degrees. The frequencies increased in steps of powers of the square root of 2 from .25 to 16 cycles/degree for three different orientations-vertical, 45 degrees and horizontal giving a total of 39 channels.
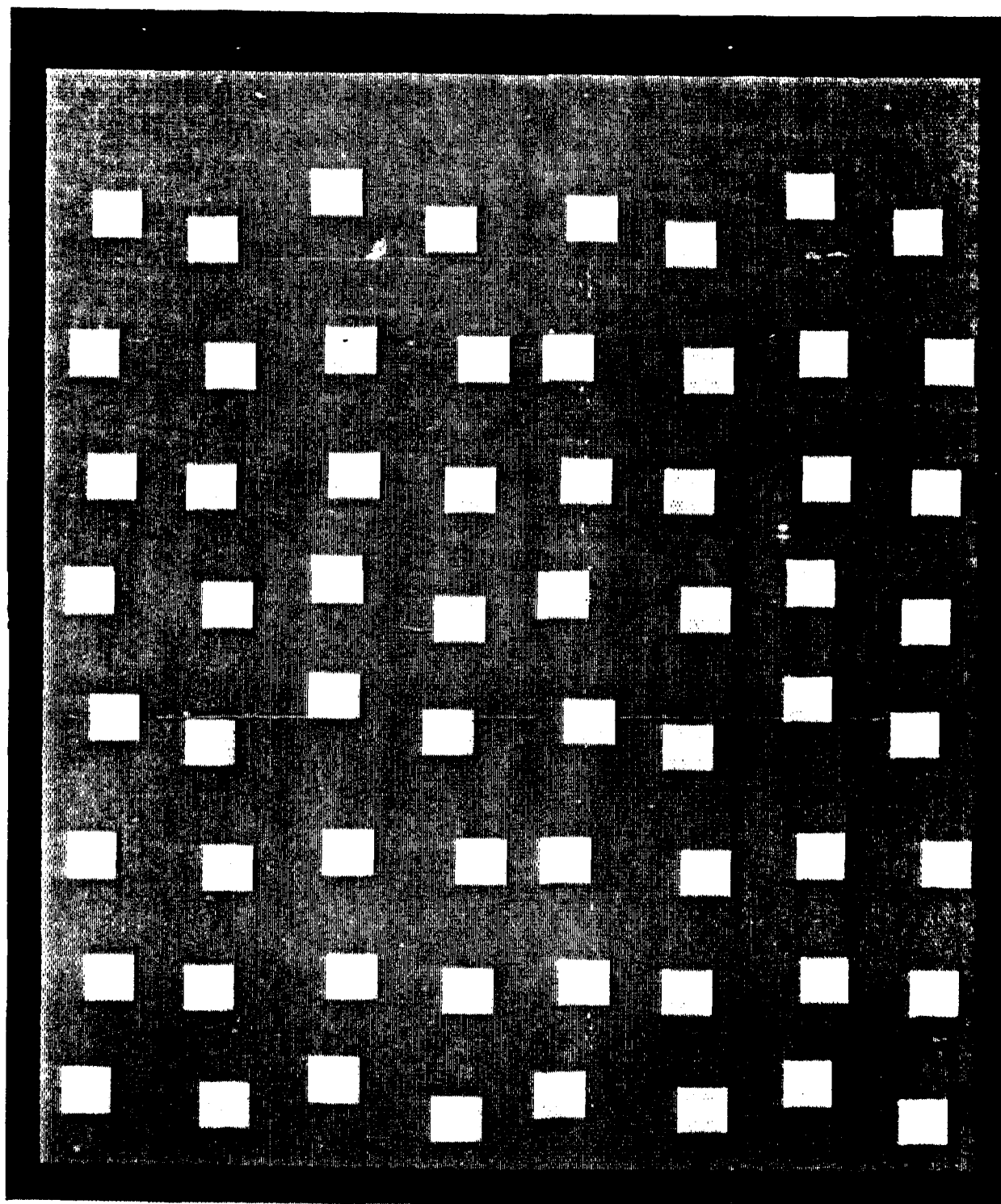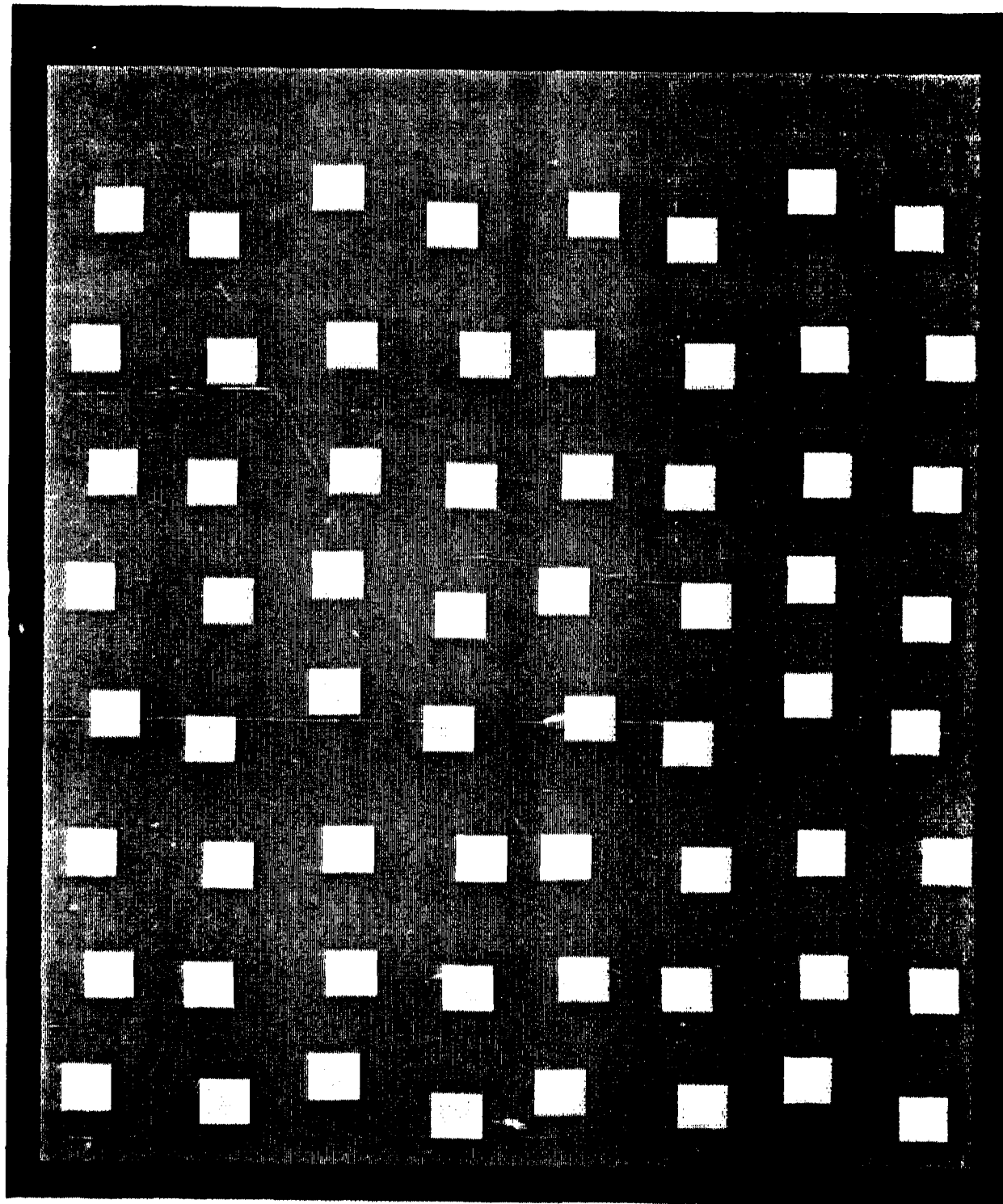
Figure 1

Figure 2

2.1.3 *Bar, Pedestal, I-Beam, Grating, Center-Surround Patterns*

Nine stimulus patterns were presented. The elements composing the patterns are shown below the abscissas of the graphs in Figure 3. The top row illustrates the elements in the discrepant quadrant, and the bottom row the elements in the non-discrepant quadrants. The overall size of an elements was a square 24 pixels on a side. With the exception of Stimulus 1, the light (l) and dark (d) areas composing an element were reversed in the discrepant and non-discrepant quadrants. There were two bar patterns. The elements in the bar patterns were made up of two rectangles 12 x 24 pixels. In Stimulus 1 (Bars-Same), the bars were the same through out the display, the top bar was dark and the bottom bar was light. In Stimulus 2 (Bars-Reversed), the top bar was dark and the bottom bar light in the discrepant quadrant; in the non-discrepant quadrants the top bar was light and the bottom bar dark. There were three pedestal patterns. In Stimulus 3 (Low-Pedestal), the pedestal was 2 x 12 pixels, in Stimulus 4 (High-Pedestal), 20 x 12 pixels, and in Stimulus 5 (Pedestal-to-Top), 22 x 11 pixels. Stimulus 6 (I-Beam) had a center beam of 18 x 8 pixels and crossbeams of 3 x 24 pixels. Stimulus 7 (Grating) had a center area of 24 x 12 pixels and flanking areas of 24 x 6 pixels. There were two center-surround patterns. Stimulus 8 (Center-3) was a rectangle 18 x 16 pixels surrounded on three sides. Stimulus 9 (Center-4) was a 17 x 17 pixel square surrounded on four sides. A pixel subtended approximately 1.08 min of arc. The arrangement of the elements was the same in all patterns. Figures 1 and 2 show the I-Beam and Center-4 patterns in which the discrepant quadrant is in the upper left.

2.1.4 *Experiment 1: Background Below*

The luminance of the background was 9.8 ft-L., the lower intensity area 14.3 ft.-L. (contrast of .35), and the higher intensity area 16.3 ft.-L. (contrast of .54). Figure 3 (top left) shows the mean segregation ratings as a function of the element shape. An one-way ANOVA revealed that the main effect of element shape was highly significant ($p < .01$). The I-Beam and the center square in the Center-4 pattern are seen as figures equally readily. From a figure-ground standpoint, the segregation ratings of the I-beam and center-4 patterns would be expected to be similar since the lightness changes in figure and ground in the two patterns are the same (see Figures 1 and 2). But, as this experiment shows, they are strikingly different. The Center-4 pattern segregated strongly, mean rating of 3.3, while the I-Beam segregated weakly, mean rating of 1.6, ($p < .01$). This clearly suggests other factors, such as the activity of cells in the visual cortex that would respond differentially to the lightness reversal, are important for effortless texture segregation. The shape of a stimulus depends on figure-ground organization. The finding that interchanging figure-ground lightnesses does not necessarily yield strong texture segregation is consistent with previous findings that overall shape differences fail to predict effortless texture segregation Beck (1966, 1973, 1982).

Figure 3 (top right) shows the predicted segregation ratings when the patterns are convolved with the DOG filters. Plotted are the combined within channel differences for the standard deviations computed from all the output values (Normal), the output values greater than zero (Positive), the output values less than zero (Negative), setting the negative outputs to zero (Half-wave rectification), and taking the absolute values of the outputs (Full-wave rectification). These measures of output modulation correctly predict the order relations in the data except for the Negative statistics computed from the output values less than zero. The Normal, Positive and Half-wave rectification statistics most closely resemble the shape of the curve describing subjects'
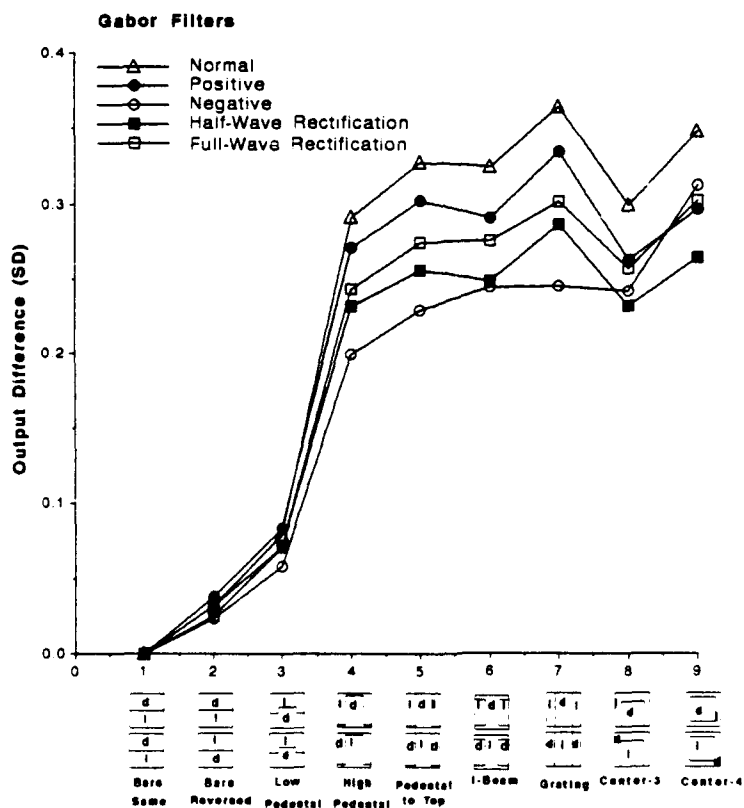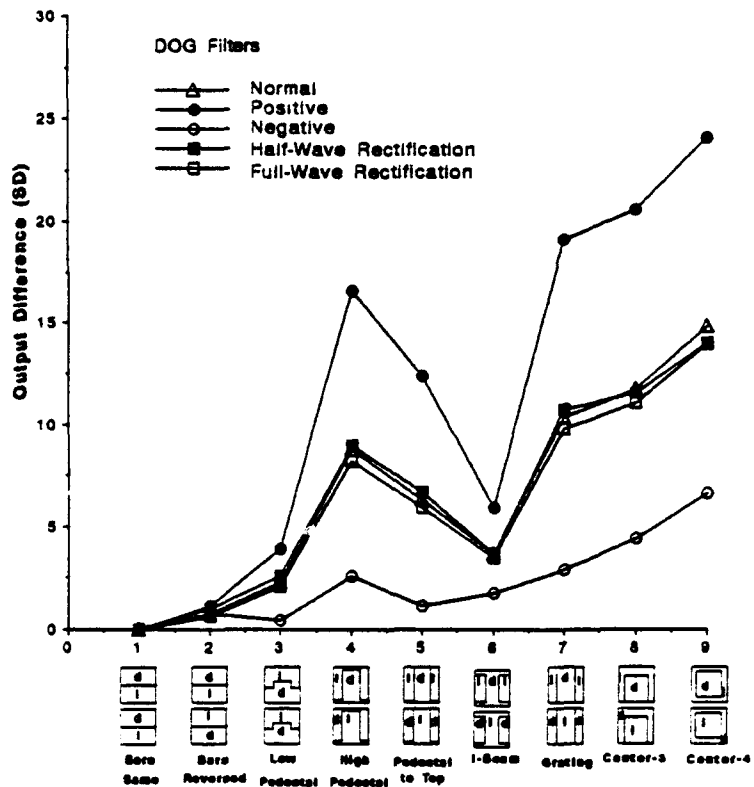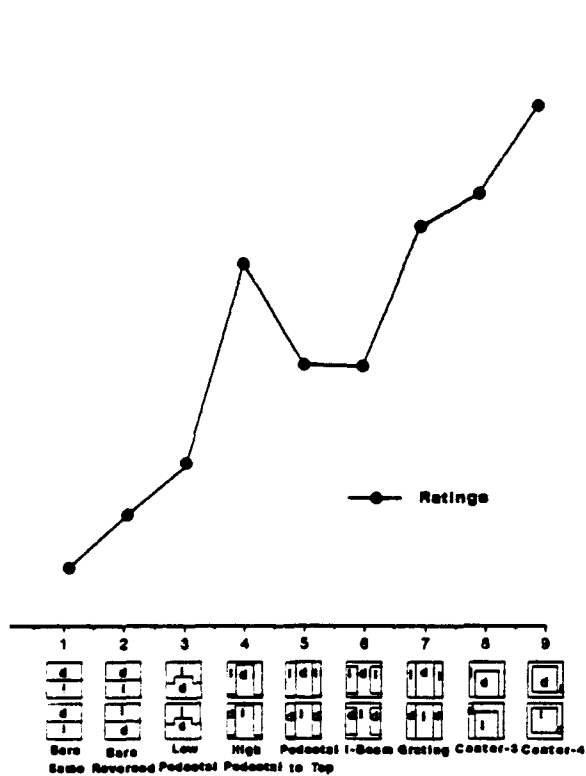
Figure 3

perceived segregation ratings. Figure 3 (bottom) shows that the outputs of the Gabor filters fail to predict the perceived segregation ratings. Why do the Dog filter outputs predict texture segregation while Gabor filter outputs fail to predict segregation? We are presently seeking to characterize the geometric features of an element which when reversed in lightness will yield large differences in output modulation when convolved with DOG and Gabor filters.

2.1.5 *Experiment 2: Background Below—Sparse vs. Dense*

This experiment studied the effect of increasing the density of elements in a pattern. The sparse patterns were the same as in Experiment 1 and had 16 shapes in each quadrant. The dense patterns had 32 shapes in each quadrant. Figures 4 and 5 show the I-beam and Center-4 dense patterns. Figure 6 (top left) shows the perceived segregation ratings for the sparse and dense patterns. The segregation ratings for the dense patterns tend to be greater than for the sparse patterns. The shapes of the overall curves, however, are very similar. A two-way ANOVA showed that the main effects of element shape ($p < .01$) and of pattern density were significant ($p < .05$). As would be expected, there was also a significant interaction between element shape and pattern density ($p < .01$). Increasing the density of a pattern did not increase perceived segregation equally for all patterns. Figure 6 shows the predicted segregation when the sparse (bottom left) and dense (bottom right) patterns are convolved with the DOG filters. The overall pattern of the outputs are highly similar. Consistent with subjects judgments of perceived segregation the outputs for the dense pattern tend to be greater than for the sparse pattern.

2.1.6 *Experiment 3: Background Between*

This experiment investigated the effects of setting the background luminance between the high and low luminance areas of the elements. The background luminance was set at 14 ft.-L. Three contrasts were used. The high and low luminances were 14.8 and 13.2 ft.-L (contrasts of +.06 and -.06), 15.8 and 12.2 ft.-L (contrasts of +.13 and -.13), and 17.5 and 10.5 ft.-L (contrasts of +.25 and -.25). Figures 7 and 8 show the I-Beam and Center-4 patterns with the background between. Figure 9 (top) shows the perceived segregation ratings. The main effects of elements shape ($p < .01$) and contrast ($p < .01$) were significant. As would be expected, there was also a significant interaction between element shape and contrast ($p < .01$). Increasing contrast did not increase rated segregation equally for all patterns. As in Experiments 1 and 2, when the background luminances were below the element luminances, the I-Beam pattern segregated less strongly than the Center-4 pattern ($p < .01$). This occurred at all contrast levels.

Figure 9 (bottom) shows the predicted segregation for the DOG filters. The Normal and Full-wave rectification statistics fail to predict perceived segregation. The Positive, Negative and Half-wave rectification statistics predict the order of the segregation ratings with two exceptions. As when the background luminance was below that of the light and dark areas of an element, the DOG filter outputs predict that the Pedestal-to-Top pattern should be perceived to segregate more strongly than the I-Beam pattern (Figures 1 and 6). When the luminance of the background was below the luminances of an element, the Pedestal-to-Top was perceived to segregate either equally or more strongly than the I-Beam (Figure 9). When the background luminance was between the luminances of the light and dark areas of an element, the I-Beam pattern was perceived to segregate more strongly than the Pedestal-to-Top pattern. This reversal was replicated in a second experiment and appears to be a consequence of the background luminance being between the
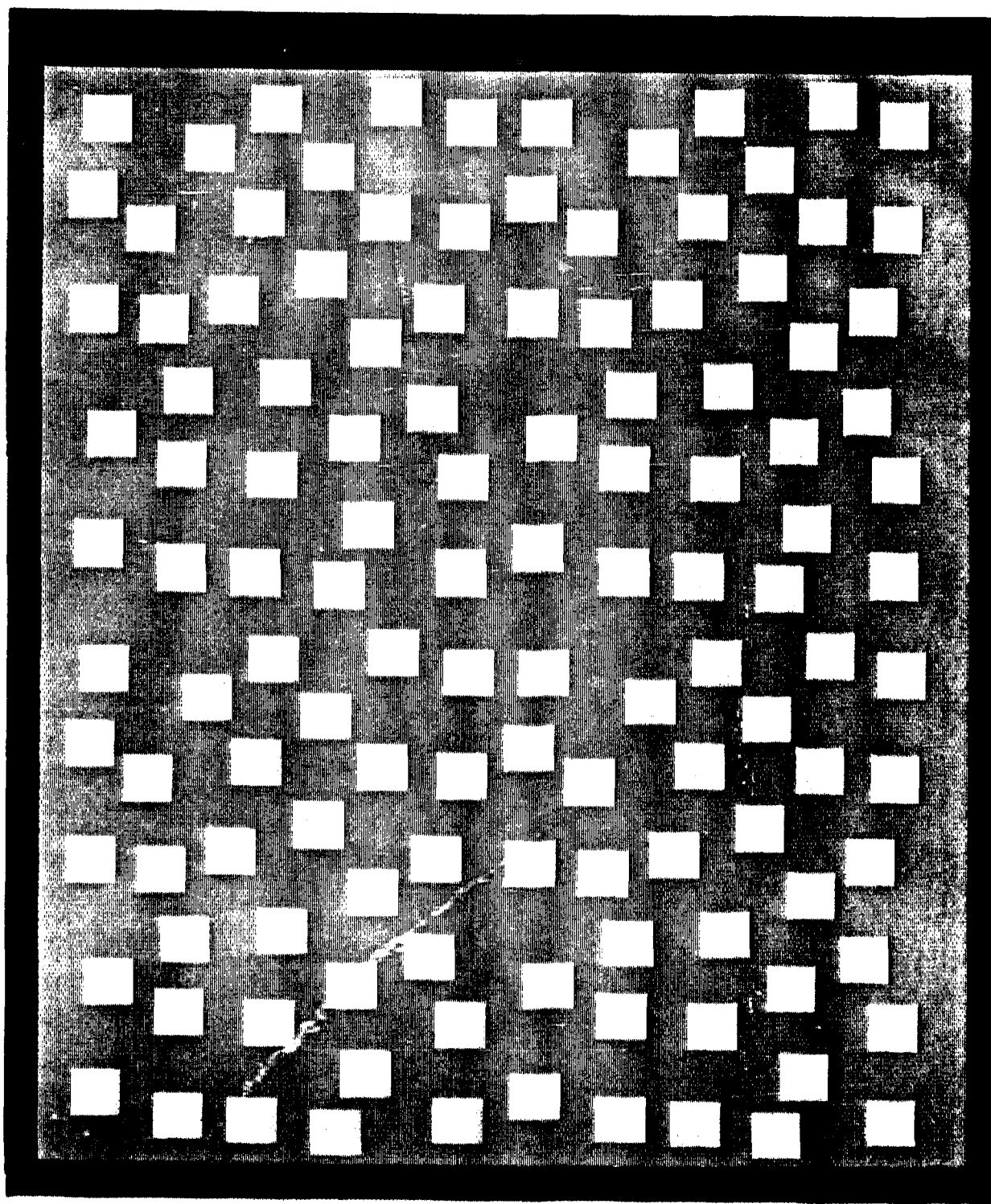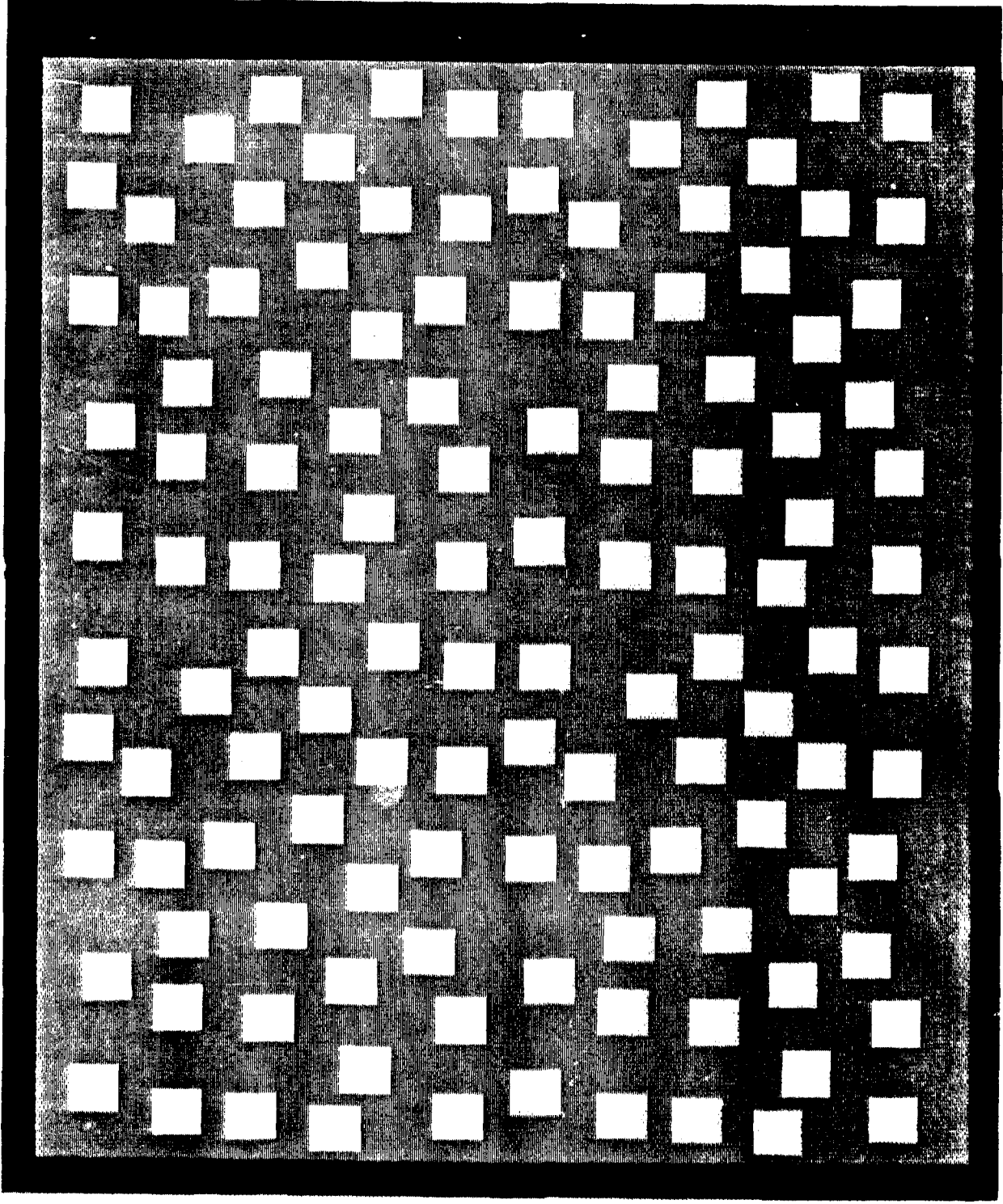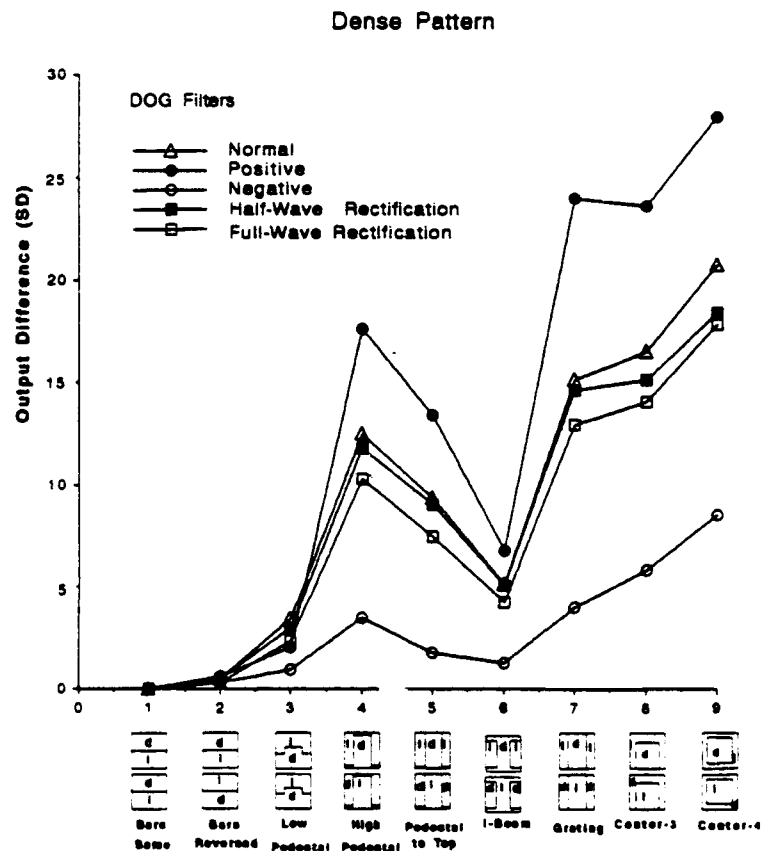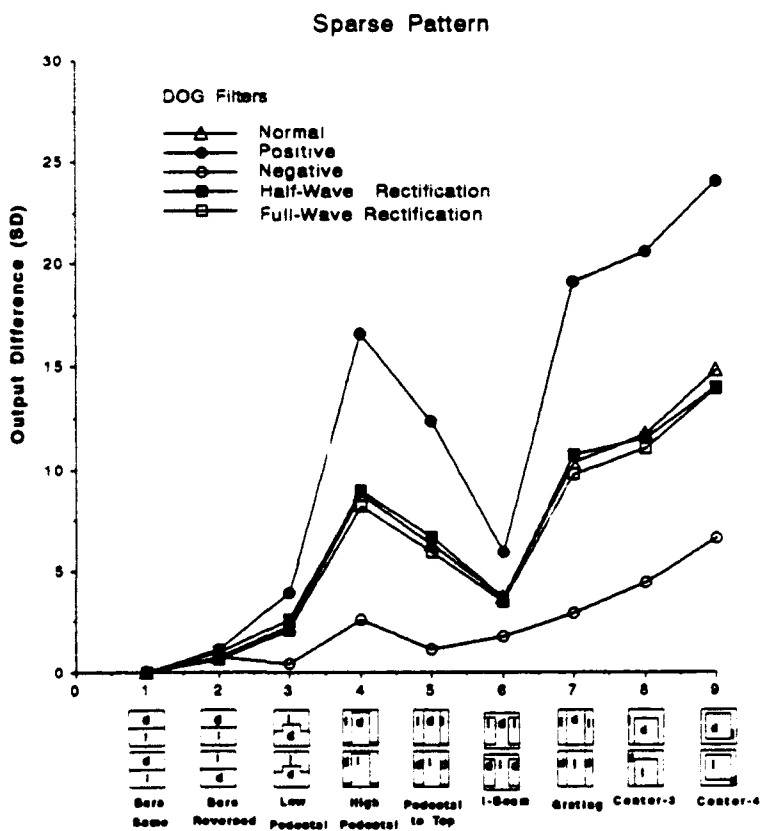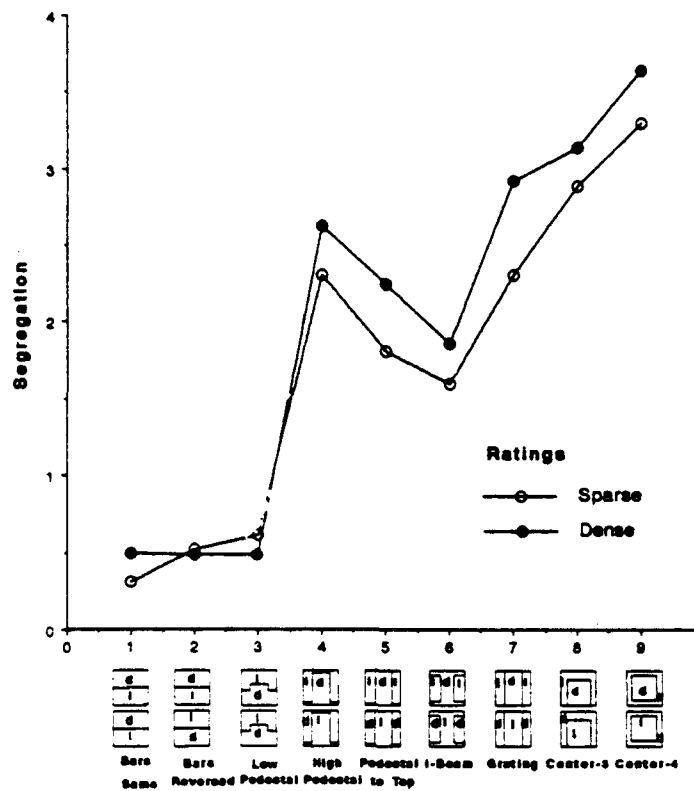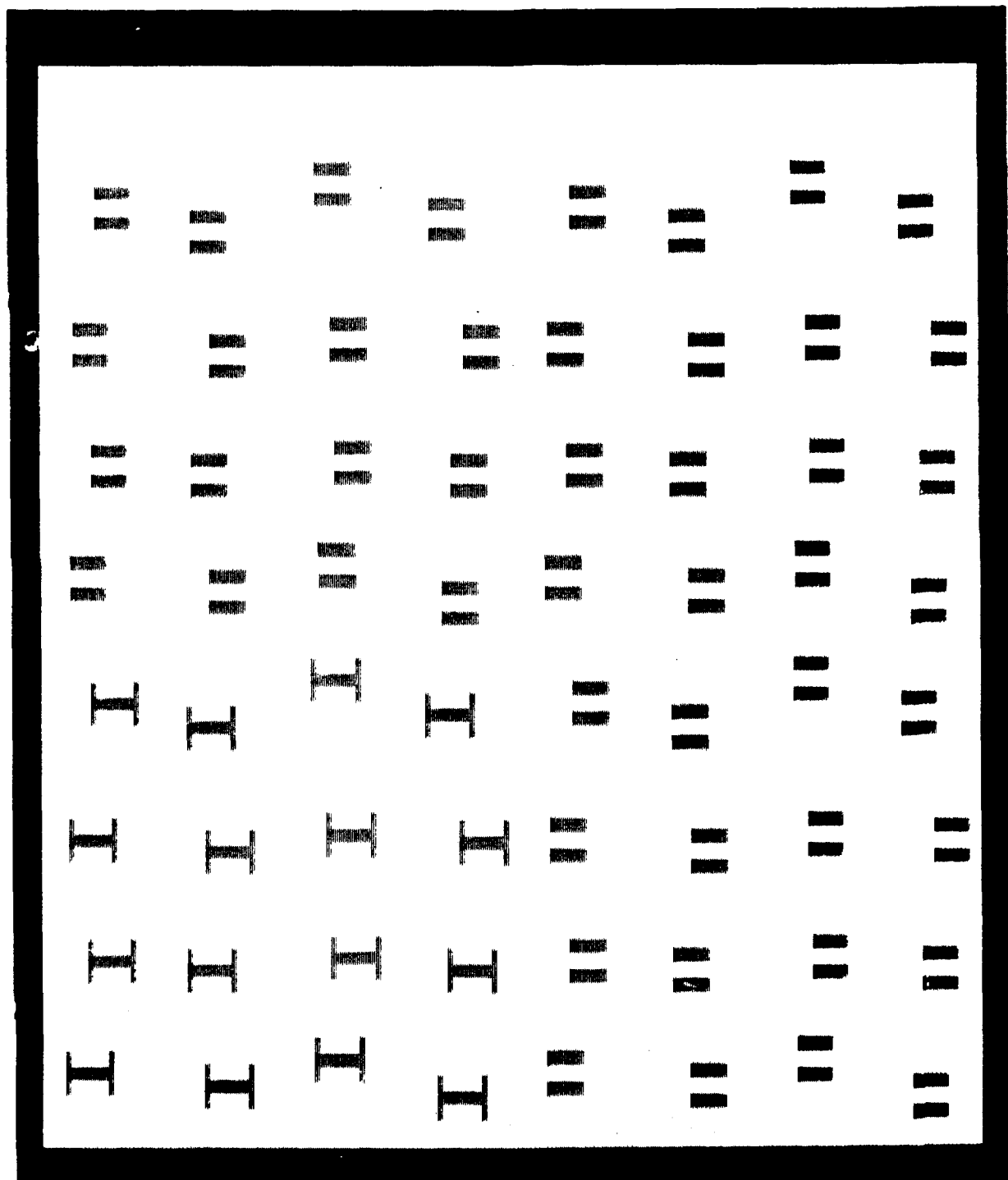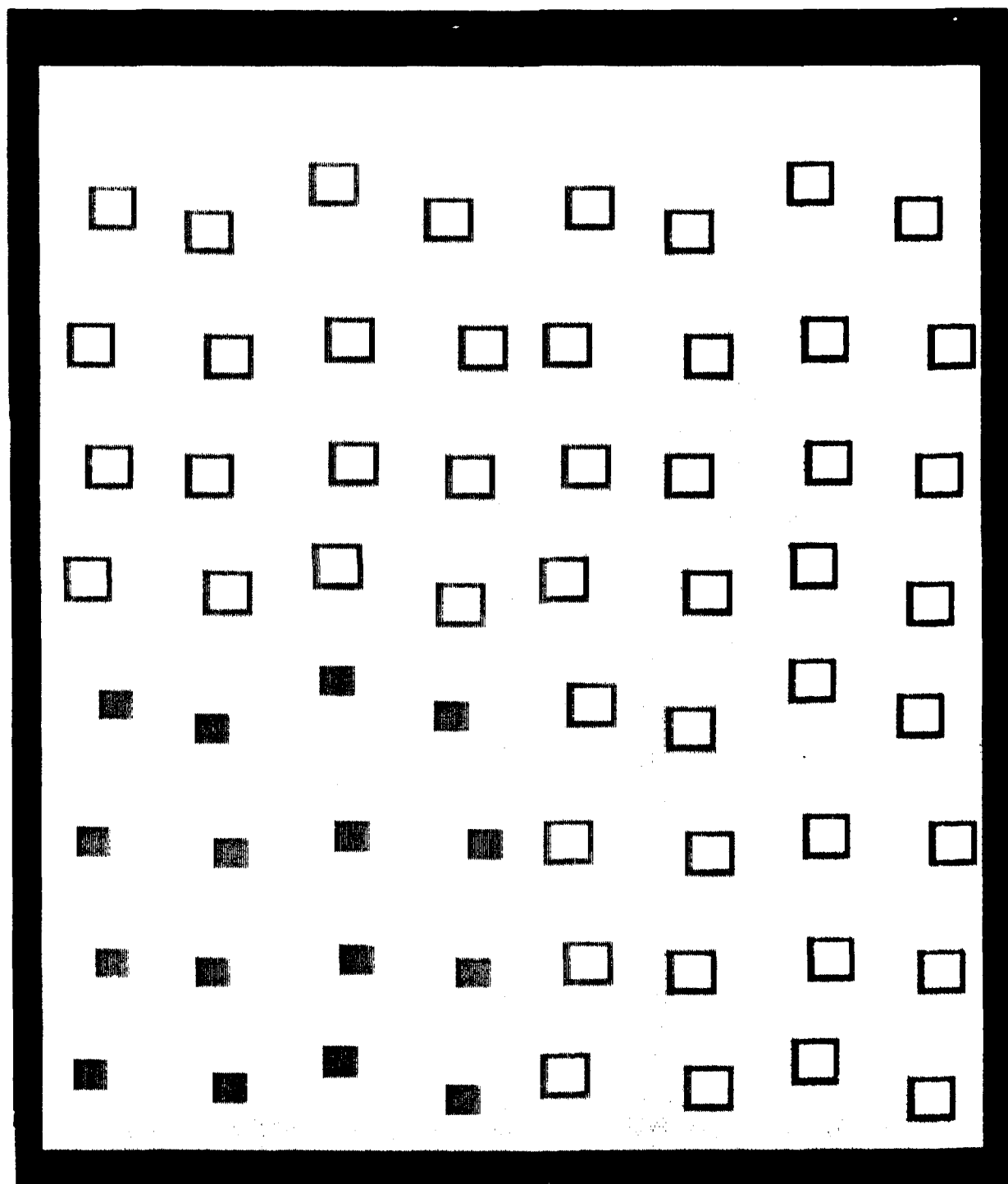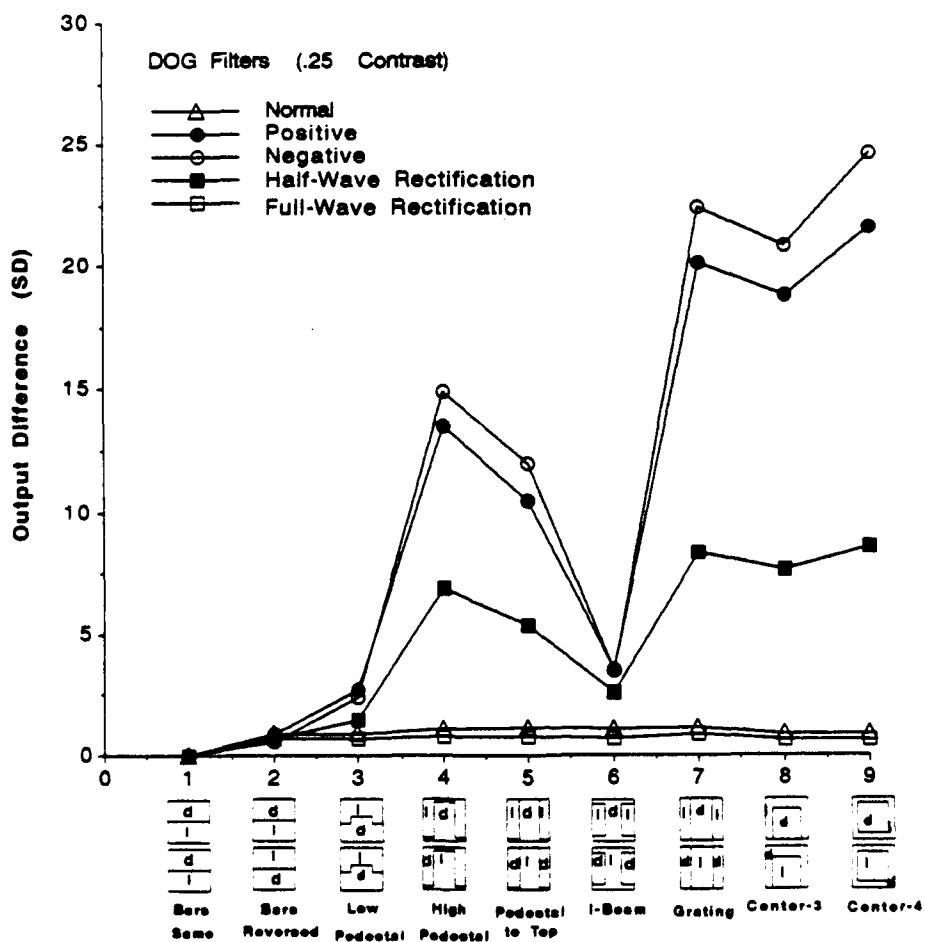
Figure 4

Figure 5

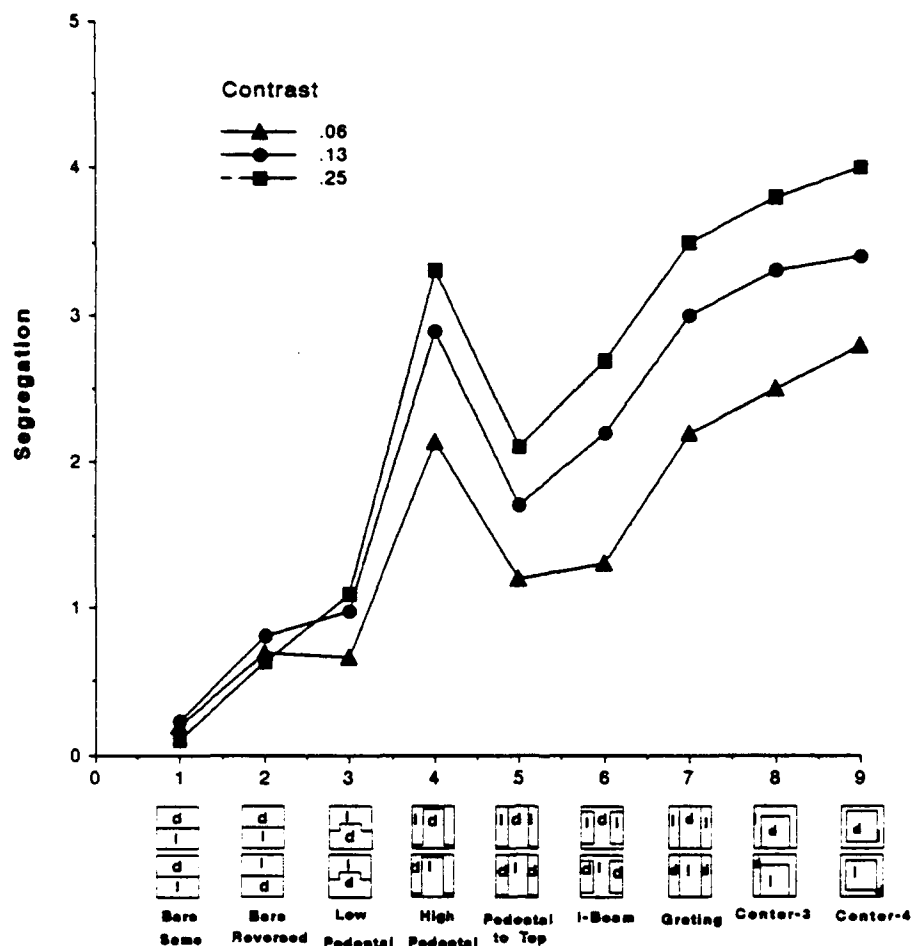Figure 6

Figure 7

Figure 8

Figure 9

luminances of the elements. The second exception is that the Center-3 square yielded stronger perceived segregation than the Grating while the DOG outputs predicted that it should be perceived to segregate less strongly or equally. When the background luminance is between the high and low luminances of an element, it may be necessary to consider the response of the center-off cells as well as the center-on cells.

2.1.7 *Experiment 4: Isoluminant Elements*

The purpose of this experiment was to determine whether the outputs of concentric receptive fields predict perceived segregation when the elements were composed of red and green areas of equal luminance. The elements composing the patterns were the same as in Experiment 1 and are shown below the abscissas of the graphs in Figure 10. The top row shows the red (r) and green (g) areas composing an element in the discrepant quadrant and the bottom row shows the red and green areas composing an element in the non-discrepant quadrants. The red and green areas of the elements in the non-discrepant quadrants were the reverse of those in the discrepant quadrant. The patterns were presented on a white and black background. Figure 10 (top) shows that perceived segregation was similar to that in Experiment 1. An one-way ANOVA revealed that the main effect of element shape was highly significant ($p < .01$). The Center-4 pattern segregated strongly (mean ratings of 3.7 and 3.8 with black and white backgrounds) while the I-beam segregated weakly (mean ratings of 1.5 and 1.2 with black and white backgrounds) ($p < .01$). We convolved the patterns with concentric filters modeled after the Type 1 center-surround cells described by T'so and Gilbert (1988). These cells have an opponent color center-surround organization-- e.g., red is excitatory in the center and green is inhibitory in the surround. However, red in the surround and green in the center have no effect. The sizes of the Type 1 filters were the same as the Dog filters. Figure 10 (bottom) shows that the combined within channel standard deviation differences are relatively successful in predicting the perceived segregation. The principal discrepancy is that the predicted segregation for the Center-3 pattern is about the same as for the High Pedestal and Grating patterns. The perceived segregation for the Center-3 pattern is greater than for the High Pedestal and Grating patterns. Further experiments have shown that the results do not depend on strict isoluminance and that segregation increased, but the shape of the function remained the same, when a luminance difference was added to a hue difference.

2.1.8 *Symmetry Patterns: Background Between*

We have begun to investigate a second set of patterns. The elements composing a pattern are shown below the abscissas in Figure 11. The elements consisted of vertical bars with approximately symmetrical horizontal extensions. The light and dark areas of the elements in the discrepant quadrant were the reverse of those in the non-discrepant quadrants. The top row shows the light (l) and dark (d) areas composing an element in the discrepant quadrant and the bottom row shows the light and dark areas composing an element in the non-discrepant quadrants. The areas of the light and dark areas of an element were equal. Figure 12 shows the pattern with element 3 (see Figure 11 bottom). Figure 11 (top) plots perceived segregation in an experiment in which the luminance of the background was midway between the luminances of the light and dark areas composing each element. The background luminance was 10 ft.-L.; the high and low luminances 20 and 0 ft.-L (contrasts of +1.0 and -1.0). The abscissa plots the average distance between the vertical bars. In general, the greater the separation between the vertical bars the stronger is the segregation. The only exception is Stimulus 6. However, in this figure we
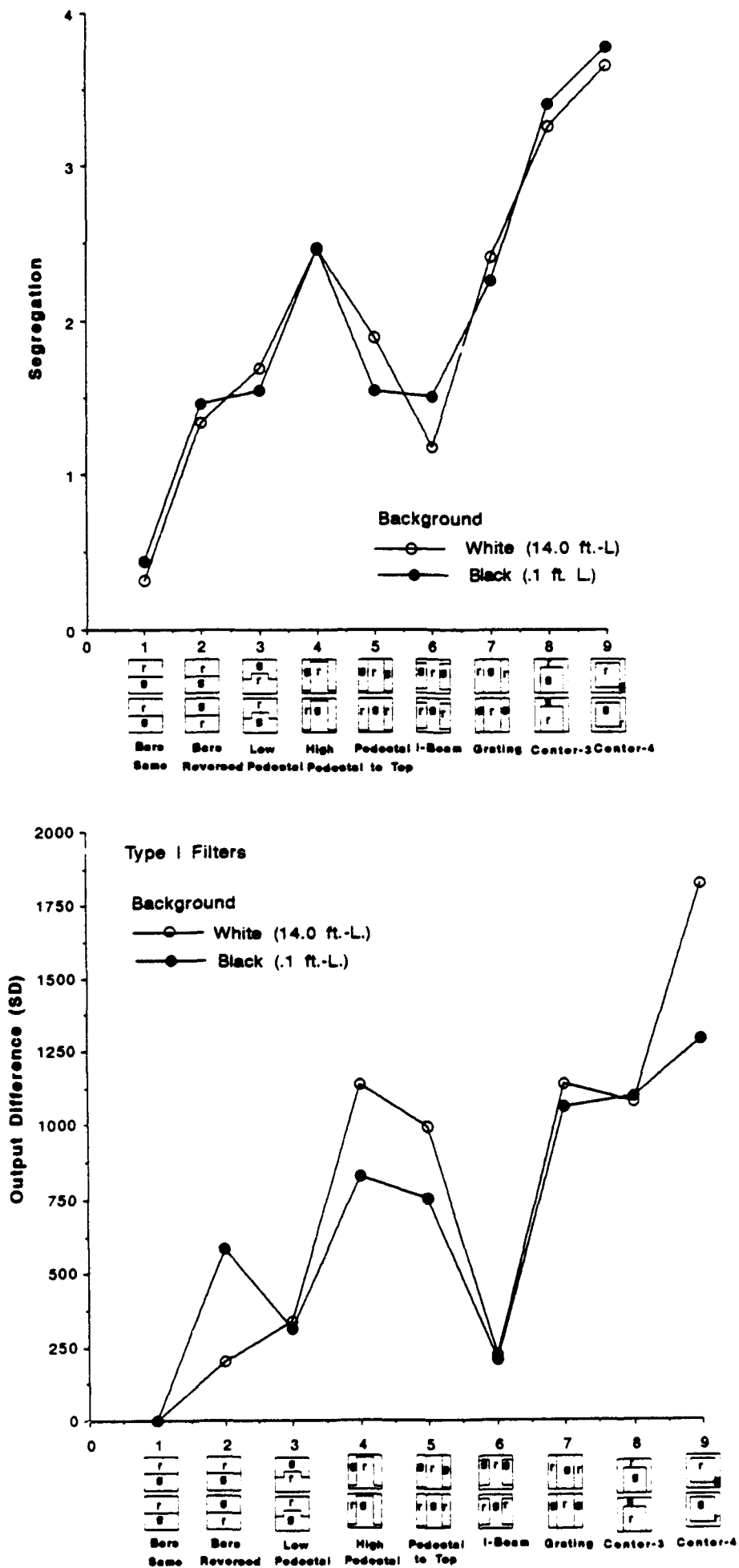
Figure 10
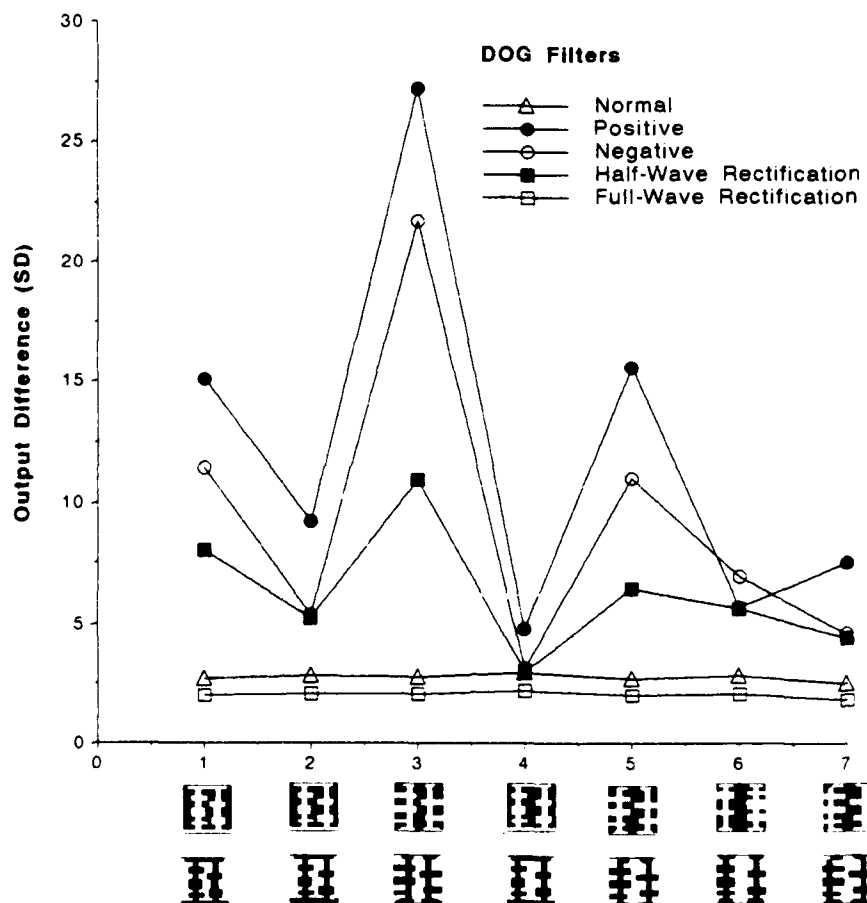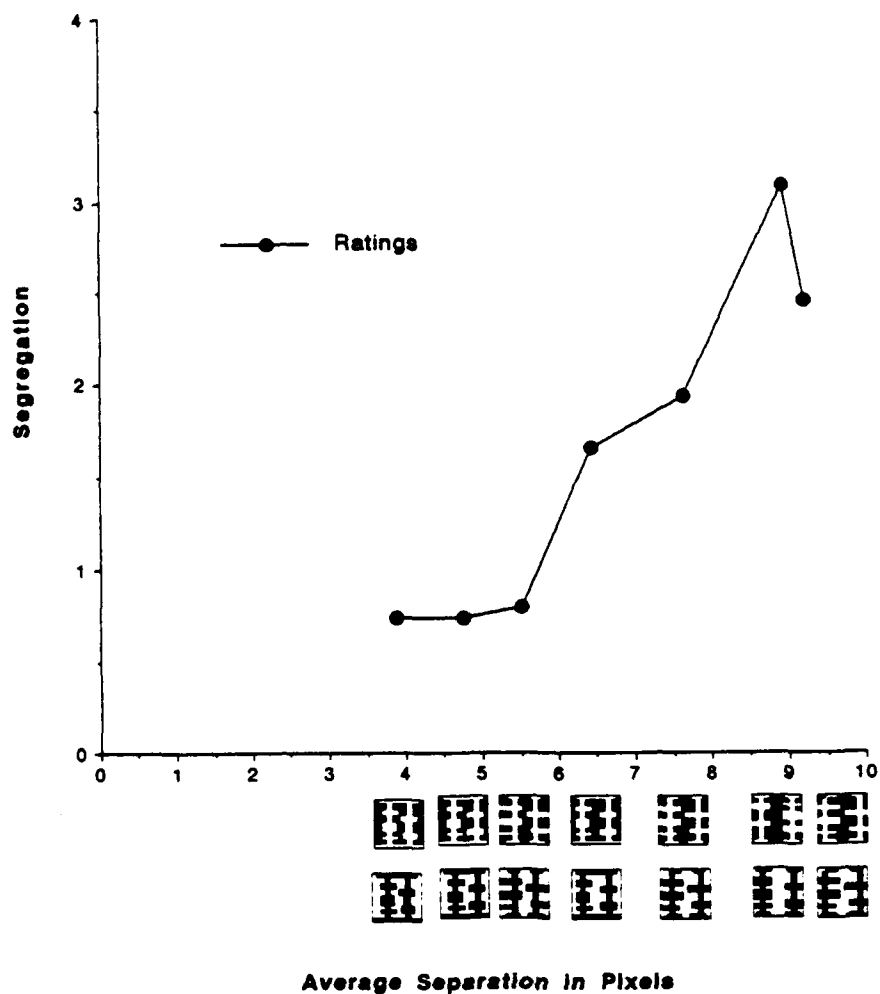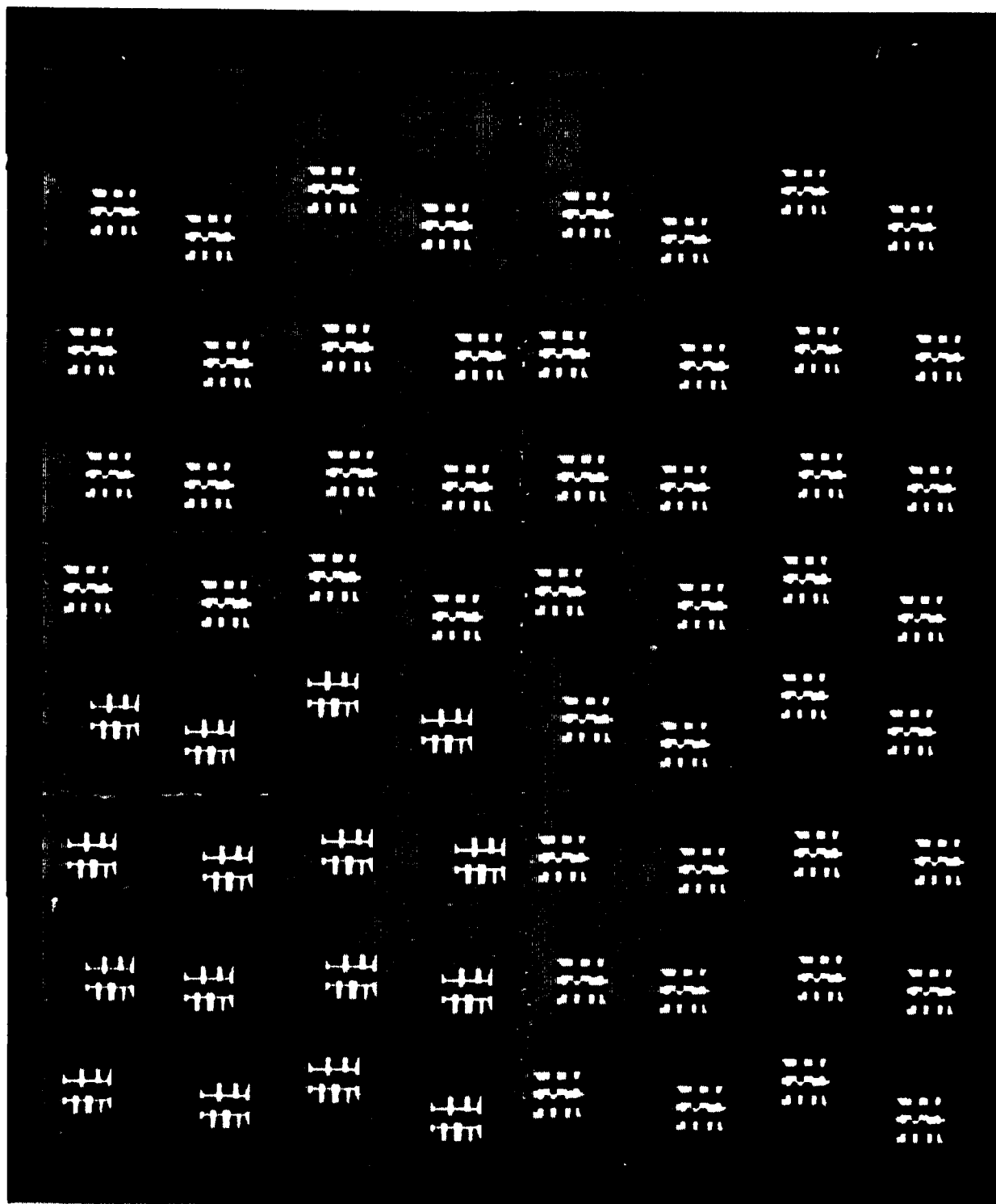
Average Separation in Pixels

Figure 11

Figure 12

inadvertently lined up the horizontal extensions giving rise to strong subjective contours. Figure 11 (bottom) shows the predicted segregation ratings when the patterns are convolved with the DOG filters. Unlike the patterns in Experiments 1 through 4, none of the statistical measures correctly predict the order relations in the data. All the elements have a strong vertical orientation and we are presently examining whether the outputs of Gabor filters will predict perceived segregation.

2.2 Grouping processes

2.2.1 *Introduction*

A commonly accepted framework for early visual processing is that there are several stages. The encoding of visual information in terms of spatial frequency channels occurs at an early stage of visual processing. Spatial frequencies compute a spatial average by means of the arrangement of excitatory and inhibitory subfields. They do not differentiate constituent elements from each other or from the background. Grouping requires the explicit representation of properties of individual elements. Though exactly how is unknown, the visual system extracts from the channel outputs the individual elements of a texture and their properties such as their size, shape, edge structure, and lightness. Experiments indicate that effortless perceptual segregation may be based on 2D grouping mechanisms. Segregation, for example, occurs for patterns that are devoid of relevant spatial frequency differences (Janez, 1984; Prazdny, 1986, Beck, Rosenfeld, & Ivry, 1989). We have shown that effortless segregation can occur as a result of the grouping of discrete elements into a line-like pattern through alignment and equal spacing of the elements (Beck, 1983; Beck, Rosenfeld, & Prazdny, 1983; Beck, Rosenfeld, & Ivry, 1989), and the similarity grouping of lightnesses (Beck, Graham, & Sutter, 1990).

2.2.2 *2D vs 3D Patterns*

An important problem is to characterize the perceptual features which result in the spontaneous and effortless segregation of patterns through grouping. Previous research with 2D perceived shapes found that texture segregation occurs strongly on the basis of simple physically defined features such as brightness, color, size and the slopes of contours and lines of the shapes (Beck, 1966, 1982; Julesz, 1962; 1984). Differences in the spatial relations between features such as the arrangement of lines in a shape that leave the slope of the component lines the same do not generally yield strong texture segregation (Beck, 1982). Enns (1988) showed that this generalization does not hold for visual search when the shapes are seen to be three-dimensional. Parallel visual search was possible for targets and distractors equated for 2D features (eg. number and slopes of lines) that differed in their perceived 3D orientation. Ramachandran (1988) found that convexity and concavity conveyed by gradients of shading yields spontaneous perceptual segregation. We conducted experiments investigating the properties of 2D and 3D perceived shapes yielding effortless region and population segregation.

2.2.3 *Experiment 1: Region Segregation*

Region segregation refers to the perceived segregation of a pattern into separate spatial regions. Chromatic and achromatic cube and circle stimuli were presented. The chromatic cube consisted of a top black, a left green, and a red right lozenge. The chromatic circles consisted of a top black, a green left, and a red right circle. The achromatic cubes and circles were black, gray,

and white as in Figures 13 and 14. The abscissa in Figure 15 identifies the four transformations of the cube and circle presented: (1) the circles and cubes in the discrepant quadrant were identical to the circles and cubes in the non-discrepant quadrants (Identical), (2) the left and right lozenges of the cubes and the left and right circles of the circle stimuli were interchanged in the discrepant quadrant (Left-Right Interchange), (3) the top and left lozenges of the cubes and the top and left circles of the circle stimuli were interchanged in the discrepant quadrant (Top-Left Interchange), (4) The cubes and circles were rotated 180 degrees in the discrepant quadrant. To anchor the upper end of the scale four patterns were presented that yielded strong segregation. The patterns consisted of red and white lozenges and ovals. The lozenges and the ovals in the discrepant quadrant were rotated 45 degrees counter clockwise from the horizontal; the lozenges and the ovals in the non-discrepant quadrants were horizontal. Figures 13 and 14 show the achromatic cube and circle stimuli in which the cubes and circles in the discrepant quadrant were rotated 180 degrees.

Figure 15 presents the results for the chromatic and achromatic stimuli (top row). A three-way ANOVA revealed that the main effects of element shape and the type of transformation were significant ($p < .01$). The cube patterns segregated more strongly than the circle patterns, and the strongest perceived segregation occurred with a 180 degree rotation. The main effect of color was not significant. The segregation ratings of the chromatic and achromatic stimuli for both cubes and circles did not differ significantly.

2.2.4 Experiment 2: Population Segregation

Population segregation refers to the perceived segregation of a pattern into two interspersed subpopulations. The discrepant and non-discrepant elements were the same as in Experiment 1. Figures 16 and 17 show the achromatic cube and circle stimuli in which the cubes and circles were rotated 180 degrees. Figure 15 (bottom row) presents the results for the chromatic and achromatic stimuli. The population segregation ratings were similar to the region segregation ratings in Experiment 1. (Region segregation and population segregation are not always similar. See Beck, Graham & Sutter (1990) for an example in which this is the case.) A three-way ANOVA revealed that the main effects of element shape and the type of transformation were significant ($p < .01$). The cube patterns segregated more strongly than the circle patterns, and the strongest perceived segregation occurred with a 180 degree rotation. The main effect of color was not significant. The segregation ratings of the chromatic and achromatic stimuli for both cubes and circles did not differ significantly.

2.2.5 Discussion

As 2D patterns, the circle and cube stimuli differ only in the arrangement of their features and therefore should give similar segregation ratings. The generally greater segregation of the cube stimuli than of the circle stimuli suggest that segregation in these textures is not based only on the 2D features of the projected image but also on the 3D representation of the projected image.

Why do changes in the arrangement of features which leave the orientations of the 2D projected lines the same yield stronger segregation with 3D than with 2D perceived figures? We do not know, but hypothesize that the differences are the result of grouping processes. For example, the lozenges in Figure 18 seen as a 2D pattern do not segregate strongly. Proximity grouping of the white, gray, and black lozenges occurs. Similarity grouping of the lozenges by
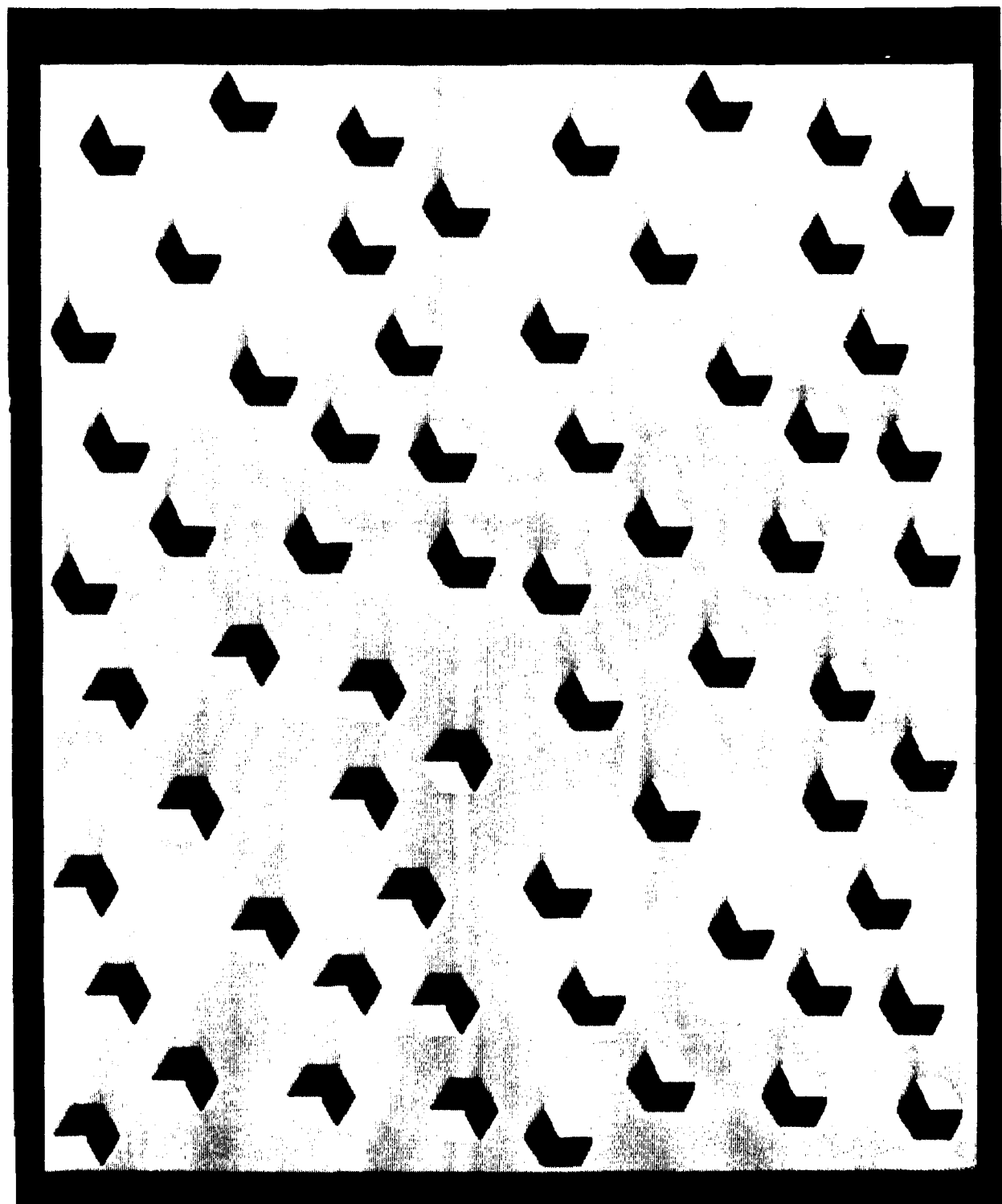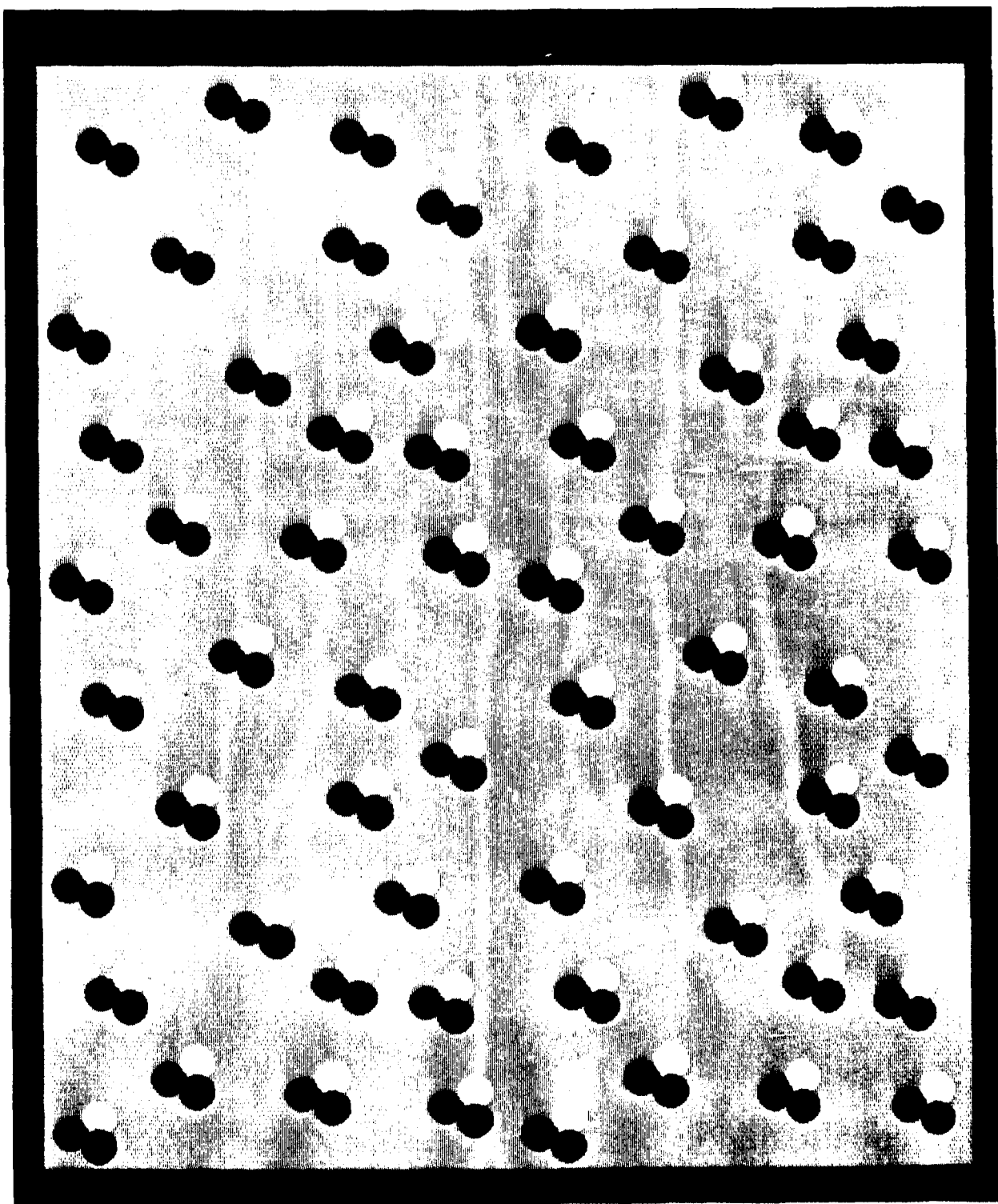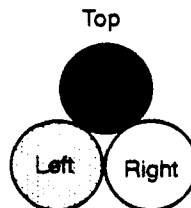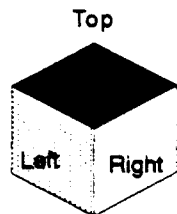
Figure 13

Figure 14
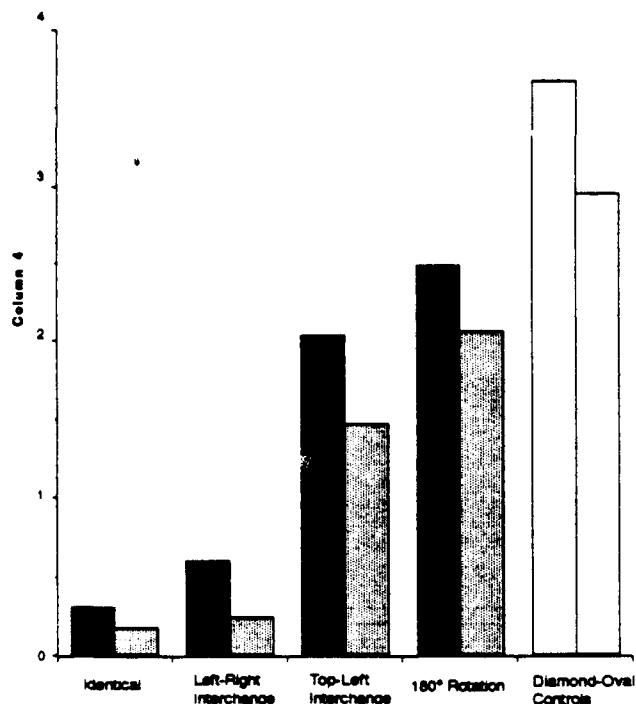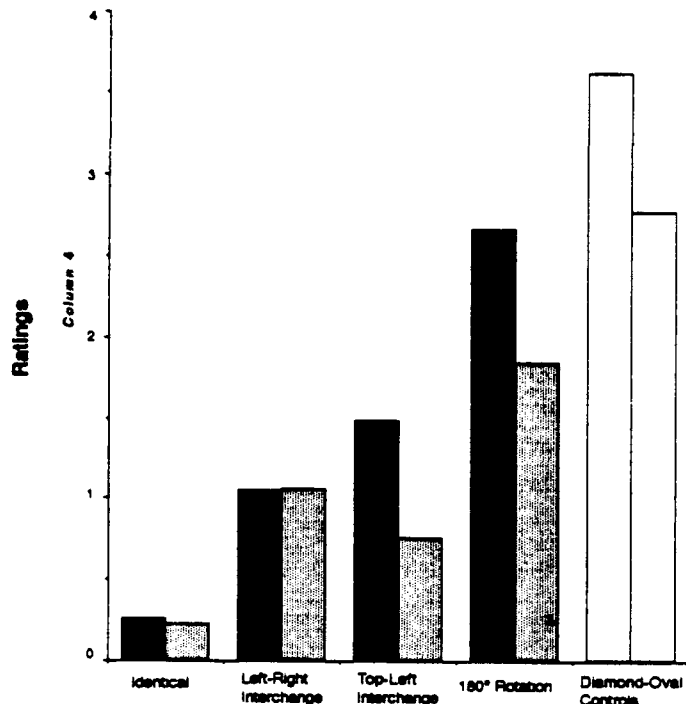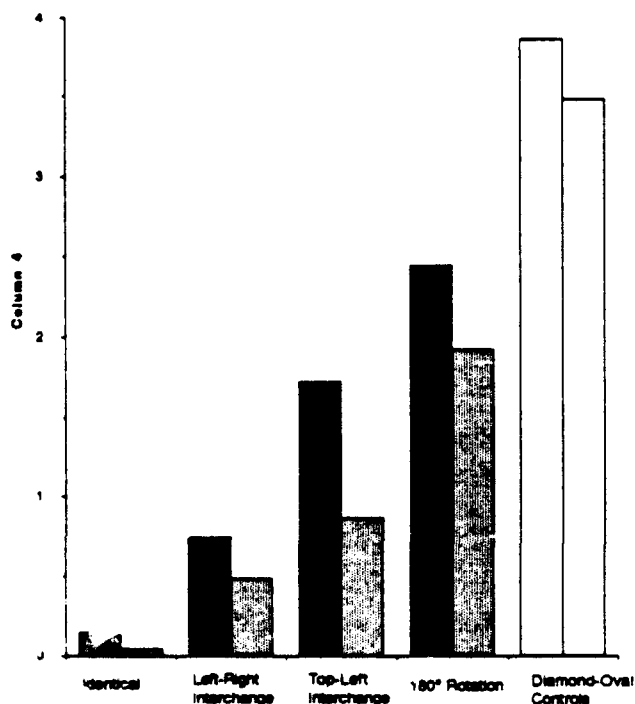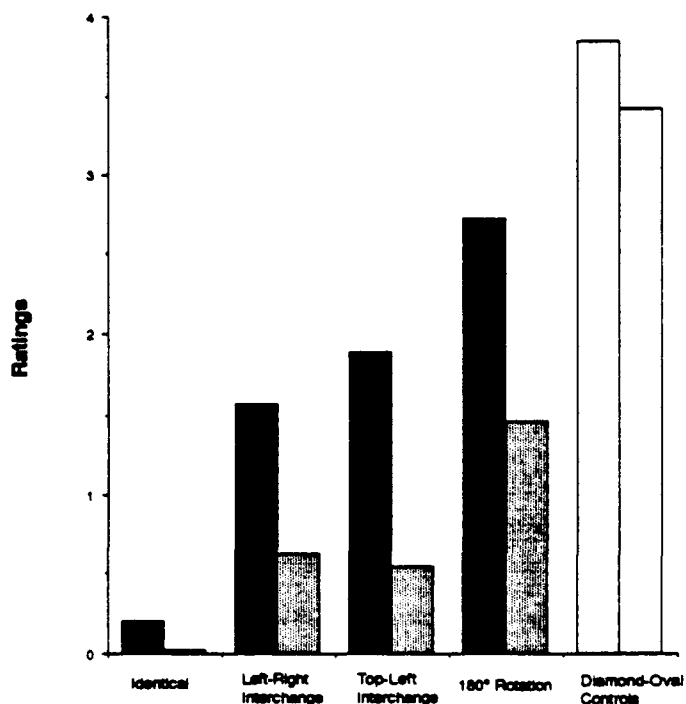
Figure 15

Figure 16

Figure 17

Figure 18

lightness, however, also occurs and interferes with the segregation of the discrepant quadrant. As a 2D pattern, the slants of the lozenges in perceptual space are the same, i.e. they are in the frontal plane. Pointing of figures up and down in 2D space is not generally salient and requires focussed attention (Beck, 1982). When the lozenges are seen as the sides of a box, the slan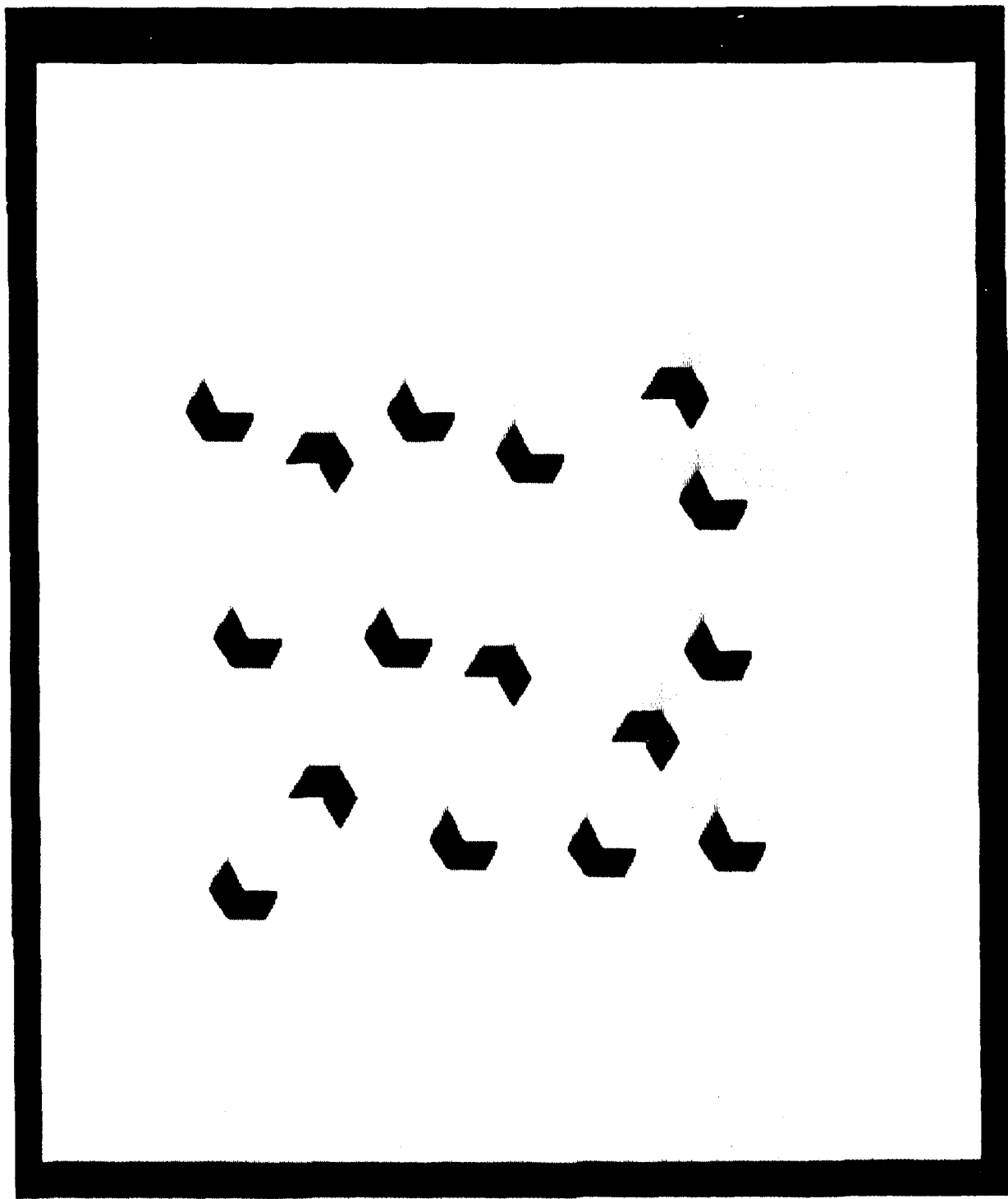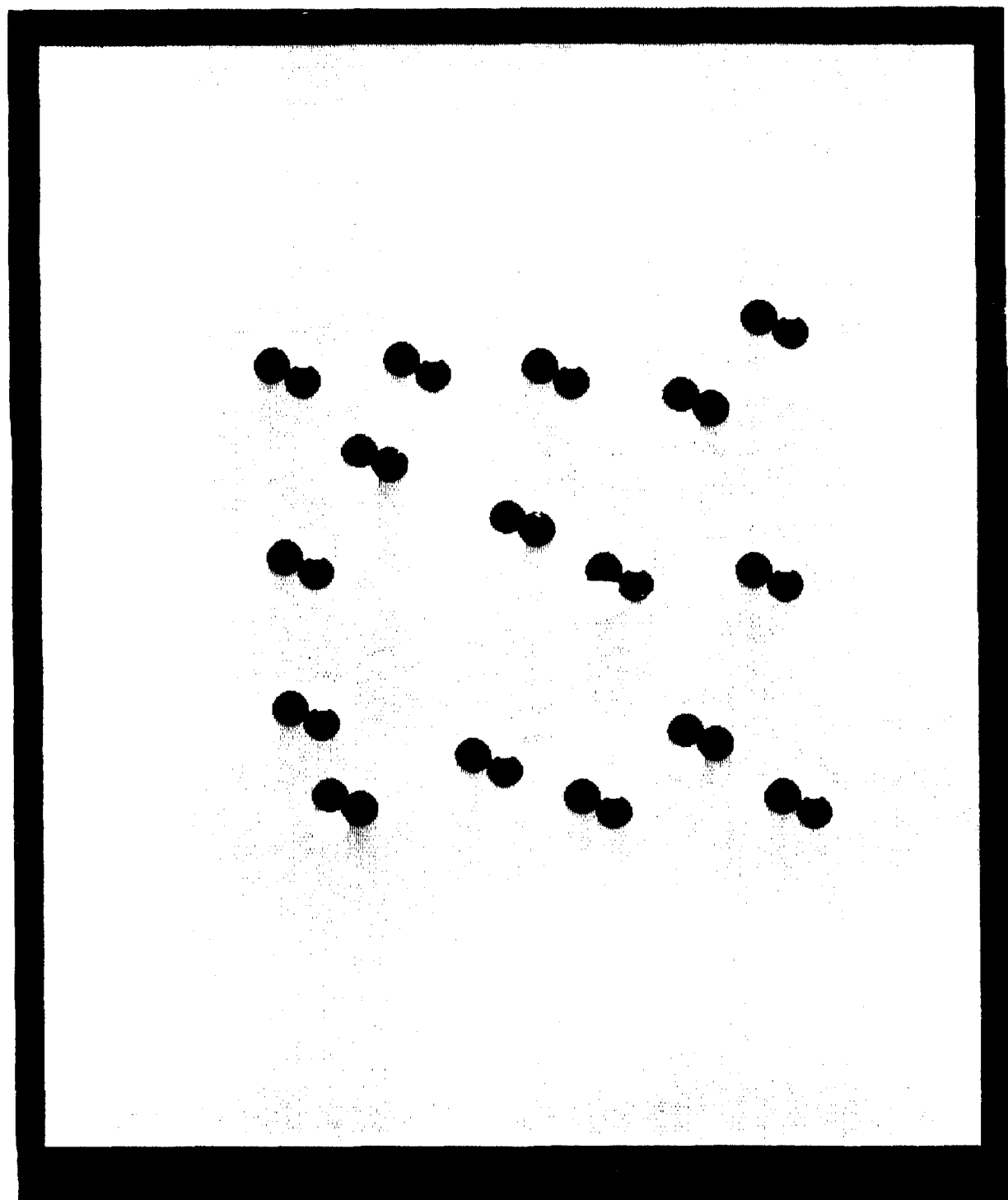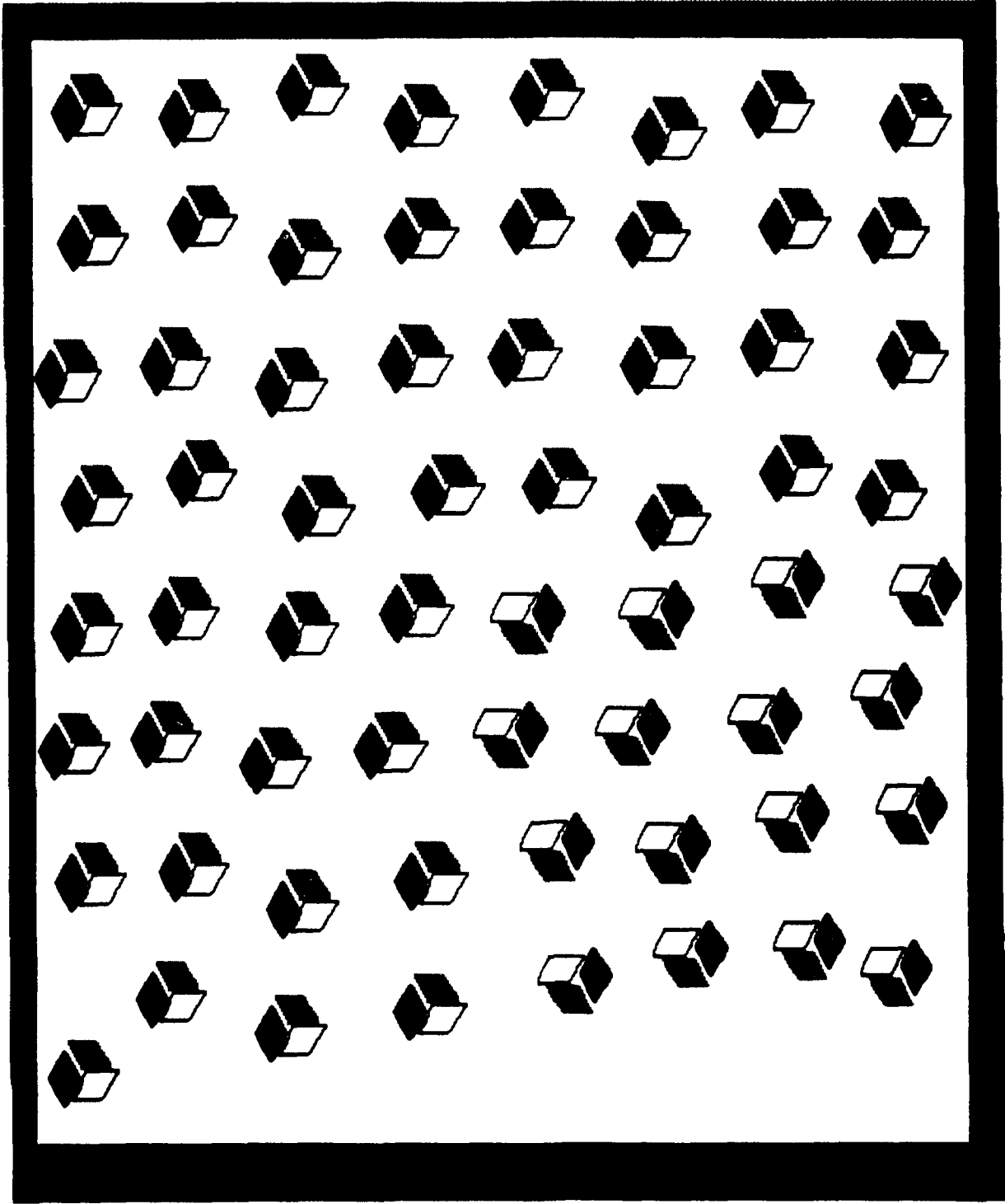ts of the lozenges in perceived 3D space differ. It is possible that this both makes the pointing of objects in 3D space more salient and reduces the tendency to group lozenges of similar lightness across figures. As a consequence, the discrepant quadrant segregates. What is suggested is that the increased segregation is due to the introduction of new grouping processes. A 3D representation makes explicit the orientations of object surfaces enabling the grouping of objects by the similarity of their surface orientations, e.g., the directions of their surface normals.

Spontaneous texture segregation requires parallel processing (Beck, 1972). Parallel processing can occur without attention (Braun & Sagi, 1990) or with attention (Pashler, 1987). Pashler (1987), for example, found that subjects could attend to up to eight items and process them in parallel. Attention more broadly spread augments the processing of information over a larger area but requires more salient stimulus differences than when focussed more narrowly. We conjecture that texture segregation based on differences in the modulation of channel outputs and the 2D grouping of contour, lightness, and other simple properties do not require attention. Texture segregation based on the orientation of 3D surfaces, however, depends on shape information and requires attention.

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Graham, N., Beck, J., & Sutter, A. (1990). Contrast and spatial variables in texture segregation: testing a complex spatial frequency model. Submitted for publication.

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5. INVITED TALKS (reporting AFOSR research, 1989-1990)

12th European Conference on Visual Perception, Zichron Yaakov, Israel, 1989, "Two cases of preattentive segregation: regions and lines."

Second International Conference on Visual Search, Durham, England, 1990, The British Aerospace Lecture "Effortless visual segregation: stimuli, processes, and representations."

Boston University Colloquium, 1990, "Two cases of preattentive segregation: regions and populations."

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